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Carbon-to-Oxygen Ratios in M dwarfs and Solar-type Stars

Tadashi Nakajima¹

Astrobiology Center, 2-21-1, Osawa, Mitaka, Tokyo, 181-8588, Japan

tadashi.nakajima@nao.ac.jp

and

Satoko Sorahana

*Department of Astronomy, Graduate School of Science, The University of Tokyo, 7-3-1
Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*

sorahana@astron.s.u-tokyo.ac.jp

ABSTRACT

It has been suggested that high C/O ratios (> 0.8) in circumstellar disks lead to the formation of carbon dominated planets. Based on the expectation that elemental abundances in the stellar photospheres give the initial abundances in the circumstellar disks, the frequency distributions of C/O ratios of solar-type stars have been obtained by several groups. The results of these investigations are mixed. Some find C/O > 0.8 in more than 20% of stars, and C/O > 1.0 in more than 6%. Others find C/O > 0.8 in non of the sample stars. These works on solar-type stars are all differential abundance analysis with respect to the Sun and depend on the adopted C/O ratio in the Sun. Recently a method of molecular line spectroscopy of M dwarfs with which carbon and oxygen abundances are derived respectively from CO and H₂O lines in the K band, has been developed. The resolution of the K band spectra is 20,000. Carbon and oxygen abundances of 46 M dwarfs have been obtained by this non-differential abundance analysis. Carbon-to-oxygen ratios in M dwarfs derived by this method are more robust than those in solar-type stars derived from neutral carbon and oxygen lines in the visible spectra due to the difficulty in the treatment of oxygen lines. We

¹National Astronomical Observatory of Japan, 2-21-1, Osawa, Mitaka, Tokyo, 181-8588, Japan

have compared the frequency distribution of C/O distributions in M dwarfs with those of solar-type stars and have found that low frequency of high C/O ratios is preferred.

Subject headings: stars: abundances — stars: low mass

1. Introduction

The study of elemental abundances in the stellar atmosphere is an important part of modern astronomy. Carbon and oxygen are among the most important elements and the carbon-to-oxygen ratio is expected to be the essential parameter of the atmosphere of the star hosting planets, which controls the nature of the planets. In the early 2000’s, possible existence of carbon dominated planets with carbon dominated silicates was discussed (Gaidos 2000; Kuchner & Seager 2005).

In the early 2010’s, some determinations of the carbon-to-oxygen ratios in solar-type stars found that $\sim 25\%$ of nearby stars have $C/O > 0.8$ and $\sim 8\%$ have $C/O > 1.0$ (Bond et al. 2010; Delgado Mena et al. 2010; Petigura & Marcy 2011). Bond et al. (2010) suggested that the mineralogy of planets formed in the environmental gas with $C/O > 0.8$ will make carbon dominated rocky planets, rather than oxygen dominated planets. These large fractions of high C/O ratio stars were criticized by Fortney (2012) who pointed out some issues. First the frequency of high C/O is inconsistent with relatively small fraction of dwarf carbon stars ($< 10^{-3}$) in large samples of low-mass stars. Second, these high C/O ratios are overestimated. The possible reasons for this overestimation are a high C/O ratio for the Sun used for differential abundance analysis and the treatment of a Ni blend that affects the O abundance.

A careful analysis of carbon and oxygen abundances of FG main sequence stars in the solar neighborhood was presented by Nissen et al. (2014) by taking into account the non-LTE effects in the model atmosphere and a critical analysis of the Ni blend to the forbidden [OI] line at 6300Å. Among 66 nearby disk stars for which $\lambda 7774$ OI triplet was analyzed with the non-LTE analysis, no star with $C/O > 0.8$ was found. Nissen et al. (2014) conclude that C/O does not exceed 0.8, and this result seems to exclude formation of carbon dominated planets.

Star formation history of M dwarfs is expected not to be so different from that of solar-type stars and they can also be used as probes of high C/O in the solar neighborhood. The spectra of M dwarfs include absorption bands of O-containing molecules such as TiO, VO, and CaOH, which are sensitive to the available O abundance, and hence C/O. In a two

dimensional space span by TiO and CaH indices, Gaidos (2015) and Gizis et al. (2016) plot a sequence of M dwarfs from which a small number of stars deviate in the direction of higher C/O. Gaidos (2015) estimates that high C/O ~ 1 stars constitute less than 6×10^{-4} of M dwarfs with 99% confidence, while Gizis et al. (2016) show that a high C/O ratio (0.9) is less than 1%.

Recently carbon and oxygen abundances of 46 M dwarfs have been obtained respectively from CO and H₂O molecular lines derived from *K* band spectra obtained at the Subaru telescope with a resolution of 20,000 (Tsuji & Nakajima 2014; Tsuji et al. 2015; Tsuji & Nakajima 2016). In this paper, we present the C/O ratios of these M dwarfs and examine the kinematics of the sample in terms of stellar population in §2 and compare the distribution of C/O of these M dwarfs with those of solar-type stars obtained by others using the Kolmogorov-Smirnov test in §3. Implications of the comparison results are discussed in §4.

2. Abundances and kinematics of the M dwarf sample

While abundance indicators of carbon and oxygen lines in solar-type stars are sensitive to physical conditions of atmospheric models, there are numerous lines of stable CO and H₂O in the *K* band as abundance indicators in M dwarfs, which are insensitive to detailed physical conditions of atmospheric models as shown graphically in Figure 13 of Tsuji et al. (2015). However, spectroscopic analysis of M dwarfs in the *K* band has been deemed difficult due to the severe veiling of the spectra by H₂O bands, which hides the true continuum necessary to measure equivalent widths. Tsuji & Nakajima (2014) and Tsuji et al. (2015) have overcome this problem in the following manner. They first examine the nature of veil opacities and then modify the way to measure equivalent widths. The progress in molecular line database such as HITEMP (Rothman et al. 2010) has reached the point that it allows the evaluation of the pseudo-continuum level of M dwarf spectra fairly accurately. They reformulate the spectroscopic analysis so as to refer to the pseudo-continuum defined by the molecular veil opacities, in stead of referring to the true continuum

First, the determination of carbon abundance from the ro-vibrational lines of the CO(2-1) band is described. Since the continuum of the observed M dwarf spectrum is depressed by numerous weak lines of H₂O, what can be seen is only the pseudo-continuum. In the case of the model spectrum of the M dwarf, not only the true continuum, but also the pseudo-continuum can easily be evaluated owing to the recently available H₂O line database. Then the analysis of the M dwarf spectrum can be performed by referring to the pseudo-continuum levels both on the observed and theoretical spectra. Therefore the abundant CO lines are

superb carbon abundance indicators, since most of the carbon atoms are in CO molecules, which are stable at low temperatures. Next, the determination of oxygen abundance from the ro-vibrational lines of H₂O is described. The procedure is similar to the case of CO lines. H₂O lines in the M dwarf spectrum are heavily blended with each other and the true continuum level is hidden by the collective absorption of H₂O lines themselves. However, it is possible to perform the analysis of H₂O lines by referring to the pseudo-continuum consistently defined on the observed and theoretical spectra. In the atmosphere of cool M dwarfs, oxygen atoms are first used to form CO molecules. Then almost all the oxygen atoms left after the formation of CO molecules are used to form stable H₂O molecules, which are unaffected by the uncertainties due to the imperfection in photospheric models. Thus abundant H₂O lines are very good oxygen abundance indicators. It would be convenient if carbon and oxygen abundances for the Sun could be derived from a *K* band spectrum as for M dwarfs, but it is impossible, since CO and H₂O molecules dissociate in the atmosphere of the Sun.

The derived carbon and oxygen abundances which are compiled from Tsuji & Nakajima (2014); Tsuji et al. (2015); Tsuji & Nakajima (2016) for 46 M dwarfs are given in Table 1. One of the important characteristics of this data set is that none of the M dwarfs has a C/O ratio greater than 0.8.

The sample M dwarfs are nearby ($d < 20$ pc), and expected to be mostly thin disk stars in terms of stellar population. To confirm this expectation explicitly, we have analyzed their kinematics in the Galaxy in terms of space velocities in the local standard of rest. The space velocities are calculated from proper motions, parallaxes, and radial velocities obtained from SIMBAD using the transformation formula given by Johnson & Soderblom (1987). These space velocities are given in Table 1 and a Toomre diagram is shown in Figure 1. The majority of the M dwarfs show thin disk kinematics except for a couple of stars showing marginally thick disk kinematics ($100 < |\mathbf{V}_{LSR}| < 120$ km s⁻¹). There is no star showing halo kinematics.

3. The Kolmogorov-Smirnov test for C/O ratios obtained by different investigators

3.1. Two-sample Kolmogorov-Smirnov test

Brief introduction to the Kolmogorov-Smirnov (K-S) test is given below (Press et al. 1988). The two-sample K-S test is applicable to a pair of unbinned distributions that are functions of a single independent variable. In our case, the independent variable is the

C/O ratio of a star. We would like to know whether two sets of data are drawn from the same parent distribution function, or from different distribution functions. The procedure in statistics is itemized in the following.

- (i) We first set the null hypothesis that data set 1 and data set 2 are derived from the same parent distribution.
- (ii) We calculate the cumulative probability distribution $S_{N_1}(x)$ of data set 1 and the cumulative probability distribution $S_{N_2}(x)$ of data set 2.

The cumulative distribution $S_N(x)$ is obtained as follows. If there are N data points located at $x_i, i = 1, \dots, N$, which are sorted into ascending order, $S_N(x)$ is the function giving the fraction of data points to the left of x . $S_N(x)$ is constant between consecutive x_i 's and it jumps by the constant $1/N$ at each x_i .

- (iii) Different estimates of cumulative distribution function are given by different data sets. However, all cumulative distribution functions agree at the smallest value of x where they are zero, and at the largest value of x where they are unity. The smallest and largest values of x might be $\pm\infty$. Therefore the distributions are distinguished by the behavior between the largest and smallest values.

- (iv) We obtain the statistic, Kolmogorov-Smirnov D : It is defined as the maximum value of the absolute difference between two cumulative distribution functions.

Thus for comparing two different cumulative distribution functions, $S_{N_1}(x)$ and $S_{N_2}(x)$, the K-S statistic is

$$D = \max_{-\infty < x < +\infty} |S_{N_1}(x) - S_{N_2}(x)|. \quad (1)$$

- (v) The K-S statistic is useful because we can calculate its distribution in the case of null hypothesis that data sets are drawn from the same distribution. Therefore any nonzero value of D is significant. The significance level of observed value D (as a disproof of the null hypothesis) or the probability that D greater than this observed value is obtained by chance, is given by the formula,

$$\Pr \left(\sqrt{\frac{N_1 N_2}{N_1 + N_2}} D > z \right) = 2 \sum_{j=1}^{\infty} (-1)^{j-1} \exp(-2j^2 z^2), \quad (2)$$

where N_1 is the number of data points in S_{N_1} and N_2 is that in S_{N_2} and the right hand side is a monotonically decreasing function of z .

(vi) For a significance level of 1% (probability = 0.01), if

$$\sqrt{\frac{N_1 N_2}{N_1 + N_2}} D > 1.62, \quad (3)$$

we disprove the null hypothesis and conclude that the two cumulative distributions are derived from different parent distributions.

(vii) On the other hand, failing to disprove the null hypothesis, only shows that the data sets can be consistent with a single parent distribution function.

3.2. Data sets of interest

We compare using the K-S test pairs of data sets of cumulative distributions of C/O ratios. The five data sets of C/O ratios we consider are the following.

(a) M dwarfs of this work (46 data points).

Carbon and oxygen abundances have been determined with respect to hydrogen abundance. These are not the result of a differential abundance analysis with respect to the Sun. There is no assumption on the C/O ratio of the Sun.

(b) Takeda & Honda (2005) (149 data points)

The sample consists of nearby disk F, G, and K dwarfs and subgiants. The abundances of carbon are determined from CI 5052 and 5380 lines. Non-LTE effect is taken into account for these permitted lines. They examine three oxygen indicators, the [OI] 6300 (forbidden line), OI 6158 and OI 7774 triplet for which non-LTE effect is taken into account and decide to adopt the oxygen abundances determined from the OI 7774 triplet. Their abundance analysis is differential with respect to the Sun and they present [C/Fe] and [O/Fe] as their final product, from which [C/O] is calculated. They do not make any assumption on solar abundances of carbon and oxygen, so C/O ratios in absolute scale are not provided.

(c) Nissen et al. (2014) (66 data points)

The sample consists of F and G stars in the Galactic disk. Carbon abundances are determined from CI 5052 and 5380 lines and oxygen abundances are determined from the OI 7774 triplet for which non-LTE corrections are applied. They also analyze the [OI] 6300 (forbidden line) and find that the better result is obtained from the OI 7774 triplet. These are a product of differential abundance analysis and they use a solar C/O ratio of 0.58 (Nissen 2013) to obtain C/O ratios in absolute scale.

(d) Delgado Mena et al. (2010) (331 data points)

The sample consists of F, G, and K stars from HARPS GTO sample (Mayor et al. 2003). Carbon abundances are determined from CI 5052 and 5380 lines and oxygen abundances are determined from the [OI] 6300 forbidden line. The abundance analysis is differential with respect to the Sun. They adopt a high solar C/O ratio of 0.66 (Anders & Grevesse 1989; Nissen et al. 2002) to obtain C/O ratios in absolute scale.

(e) Petigura & Marcy (2011) (446 data points)

The sample consists of F and G stars from the SPOCS catalog (Valenti & Fischer 2005) and the N2K sample (Fischer et al. 2005). Carbon abundances are determined from CI 6587 line and oxygen abundances are from [OI] 6300 line. They adopt a solar C/O ratio of 0.63 (Scott et al. 2009; Caffau et al. 2010) to obtain C/O ratios in absolute scale.

3.3. Comparison of M dwarf distribution with others

Since the C/O ratios of M dwarfs are given in absolute scale, the data set to be compared must also be given in absolute scale. Since no solar abundance ratio is given in the work of Takeda & Honda (2005), it is excluded in this comparison. In the following, the results of comparison between pairs are described. The cumulative distributions are given graphically in Figure 2, and the parameters of the K-S test and corresponding panels in Figure 2 are summarized in Table 2.

3.3.1. (a) M dwarfs and (c) Nissen et al. (2014)

The K-S statistic $D = 0.177$ and the probability that the two data sets are drawn from the same cumulative distributions is 3.30×10^{-1} . This probability does not disprove the null hypothesis. It shows that the data sets can be consistent with being drawn from a single cumulative distribution function.

3.3.2. (a) M dwarfs and (d) Delgado Mena et al. (2010)

The K-S statistic $D = 0.528$ and the probability that the two data sets are drawn from the same cumulative distributions is 1.29×10^{-10} . This probability is significant enough to disprove the null hypothesis. It shows that the two data sets are drawn from different cumulative distribution functions. The C/O ratios of Delgado Mena et al. (2010) are apparently

higher than those of M dwarfs.

3.3.3. (a) *M dwarfs and (e) Petigura & Marcy (2011)*

The K-S statistic $D = 0.427$ and the probability that the two data sets are drawn from the same cumulative distributions is 2.60×10^{-7} . This probability is significant enough to disprove the null hypothesis. It shows that the two data sets are drawn from different cumulative distribution functions. The C/O ratios of Petigura & Marcy (2011) are apparently higher than those of M dwarfs.

3.4. Comparison among the cumulative distributions derived from differential abundance analyses

We consider that both different multiplication factors (adopted C/O ratios of the Sun) and scatters (dispersions in C/O values) may be the sources of discrepancies among the C/O distributions of different works in linear scale. To isolate the effect of scatter, we compare linear C/O ratios with respect to the Sun, $10^{[C/O]}$, calculated from logarithmic abundances, $[C/O] (= [C/H] - [O/H])$ obtained by differential abundance analyses. Since the M dwarf distribution is the result of absolute abundance analysis, it is excluded from this comparison. The cumulative distributions are given graphically in Figures 3 and 4, and the parameters of the K-S test and corresponding panels in Figures 3 and 4 are summarized in Table 3

3.4.1. (b) *Takeda & Honda (2005) and (c) Nissen et al. (2014)*

The K-S statistic $D = 0.121$ and the probability that the two data sets are drawn from the same cumulative distributions is 4.87×10^{-1} . This probability is not significant enough to disprove the null hypothesis. It shows that the data sets can be consistent with being drawn from a single cumulative distribution function.

3.4.2. (b) *Takeda & Honda (2005) and (d) Delgado Mena et al. (2010)*

The K-S statistic $D = 0.163$ and the probability that the two data sets are drawn from the same cumulative distributions is 7.26×10^{-3} . This probability is significant enough to

disprove the null hypothesis. It shows that the data sets are drawn from different cumulative distribution functions.

3.4.3. (b) *Takeda & Honda (2005) and (e) Petigura & Marcy (2011)*

The K-S statistic $D = 0.204$ and the probability that the two data sets are drawn from the same cumulative distributions is 1.40×10^{-4} . This probability is significant enough to disprove the null hypothesis. It shows that the data sets are drawn from different cumulative distribution functions.

3.4.4. (c) *Nissen et al. (2014) and (d) Delgado Mena et al. (2010)*

The K-S statistic $D = 0.234$ and the probability that the two data sets are drawn from the same cumulative distributions is 3.80×10^{-3} . This probability is significant enough to disprove the null hypothesis. It shows that the data sets are drawn from different cumulative distribution functions.

3.4.5. (c) *Nissen et al. (2014) and (e) Petigura & Marcy (2011)*

The K-S statistic $D = 0.288$ and the probability that the two data sets are drawn from the same cumulative distributions is 1.02×10^{-4} . This probability is significant enough to disprove the null hypothesis. It shows that the data sets are drawn from different cumulative distribution functions.

3.4.6. (d) *Delgado Mena et al. (2010) and (e) Petigura & Marcy (2011)*

The K-S statistic $D = 0.114$ and the probability that the two data sets are drawn from the same cumulative distributions is 1.27×10^{-2} . This probability does not disprove the null hypothesis. It shows that the data sets can be consistent with being drawn from a single cumulative distribution.

4. Discussion

4.1. C/O ratio of the Sun

We have seen in the §3.3 that the distribution of the C/O ratios in M dwarfs can be consistent with that of Nissen et al. (2014) who use the solar C/O ratio of 0.58, while it is different from those of Delgado Mena et al. (2010) and Petigura & Marcy (2011). The solar C/O ratio of 0.58 is close to 0.55 recommended by Asplund et al. (2009). If the C/O ratio of 0.55 is adopted for Takeda & Honda (2005) and Nissen et al. (2014), the K-S test with the distribution of M dwarfs gives the probabilities of both 3.30×10^{-1} , while $D = 0.156$ and 0.177 respectively for Takeda & Honda (2005) and Nissen et al. (2014). This implies that both cumulative distributions of Takeda & Honda (2005) and Nissen et al. (2014) can be drawn from the same cumulative distribution as that of M dwarfs for this solar C/O ratio.

For the originally adopted values of solar C/O ratios, the K-S test of cumulative distributions between Nissen et al. (2014) and Delgado Mena et al. (2010) gives $D = 0.441$ and the probability $= 4.73 \times 10^{-10}$. For the same K-S test between Nissen et al. (2014) and Petigura & Marcy (2011) gives $D = 0.338$ and the probability $= 3.32 \times 10^{-8}$. The discrepancies between Nissen et al. (2014) and Delgado Mena et al. (2010) and between Nissen et al. (2014) and Petigura & Marcy (2011) decrease (probabilities increase) for the cases of differential abundance analyses discussed in §3.4.4 and §3.4.5.

If the results for M dwarfs, Takeda & Honda (2005) and Nissen et al. (2014) are correct, the C/O ratios of 0.66 and 0.63 adopted respectively by Delgado Mena et al. (2010) and Petigura & Marcy (2011) are probably too high.

4.2. Source of scatter in the C/O ratios of Delgado Mena et al. (2010) and Petigura & Marcy (2011)

Since the discrepancies of cumulative distributions between Delgado Mena et al. (2010), Petigura & Marcy (2011) and Takeda & Honda (2005), Nissen et al. (2014), remain in the comparison of differential analyses in §3.4, the differences in the adopted solar C/O ratios alone do not explain these discrepancies.

As discussed by Takeda & Honda (2005) and Nissen et al. (2014), the oxygen abundances derived from the [OI] 6300 forbidden line, which is blended with Ni line, are most problematic. They compare the results from [OI] 6300 and OI 7774 triplet with non-LTE correction and conclude that the scatter of oxygen abundances derived from [OI] 6300 is greater than that from OI 7774. Delgado Mena et al. (2010) and Petigura & Marcy (2011)

both derive oxygen abundances from the [OI] 6300 forbidden line and this appears to be the major cause of the large scatter in C/O ratios.

To visualize the scatter of C/O ratios, we plot [C/O] vs. [Fe/H] diagrams for Takeda & Honda (2005) and Nissen et al. (2014) in Figure 5, and Delgado Mena et al. (2010) and Petigura & Marcy (2011) in Figure 6. Strictly speaking, Petigura & Marcy (2011) give [M/H] instead of [Fe/H], but we use [M/H] as the substitute for [Fe/H]. These diagrams exhibit the weak trend that C/O ratios are higher for higher [Fe/H], but also show the much greater scatter in Figure 6 than in Figure 5.

We also note that the different distributions of [Fe/H] and T_{eff} in the samples can contribute to the discrepancies in scatter. For example, the stars in Nissen et al. (2014) are hotter on average than those in Delgado Mena et al. (2010), while those in Petigura & Marcy (2011) are more metal-rich on average.

4.3. Indirect analysis of C/O ratios in M dwarfs

Gaidos (2015) and Gizis et al. (2016) analyze the C/O ratios in M dwarfs, indirectly from the behavior of TiO and CaH indices. In solar-type stars, the absorption lines of carbon and oxygen are so weak that the C/O ratio has little effect on the low resolution spectrum. On the other hand, M dwarf spectra are dominated by simple molecules such as TiO, VO, and CaOH, which are sensitive to the oxygen abundance available left after the formation of CO molecules and thus to the C/O ratios. Both Gaidos (2015) and Gizis et al. (2016) use the PHOENIX models (Allard et al. 2011; Husser et al. 2013) to generate model M dwarf spectra for solar composition and for high C/O ratios, from which qualitative behavior of high C/O ratio stars in the TiO vs. CaH index diagram is derived. They find that carbon-rich stars can be identified by relatively weak TiO bands for a given strength of CaH. However, metal poor subdwarfs (sdMs) exhibit similar behavior to carbon-rich stars.

The work by Gaidos (2015) is based on the expectation that at $\text{C/O} \geq 1$, TiO bands are not present, while C_2 , CN, and CH bands should appear. He analyzes the spectroscopic catalog of nearby M dwarfs, CONCH-SHELL (Gaidos et al. 2014). He finds that all carbon-rich candidates are either metal poor stars, or have systematic errors. He estimates that M dwarfs with $\text{C/O} \sim 1$ constitute less than 1.2×10^{-3} with 95% confidence. He also examines M dwarf spectra in Data Release 7 of SDSS (West et al. 2011) and sets an upper limit of 6×10^{-4} at 99% confidence.

Gizis et al. (2016) investigate the frequency of M dwarfs with $\text{C/O} = 0.9$ in the solar neighborhood. They first analyze the sample from the complete spectroscopic survey

of M dwarfs in the Northern hemisphere (Lépine et al. 2013), and find that only 2% of this sample could be M dwarfs with high C/O ratios, but many, if not all, are stars with low metallicity. Second they analyze the sample from the PMSU survey (Reid et al. 1995; Hawley et al. 1996). In this sample, M subdwarfs (sdM type) are less than 1% and this fraction is consistent with the expected numbers of metal-poor (thick disk/halo) population estimated from kinematics. Third they also analyze the SDSS sample (West et al. 2011) and find a similar result. They conclude that less than 1% of nearby M dwarfs have $0.8 < \text{C/O} < 1$.

From our analysis of C/O ratios in M dwarfs and solar-type stars, the result by Gaidos (2015) that M dwarfs with $\text{C/O} > 1$ are very rare appears to be qualitatively supported. Similarly the result by Gizis et al. (2016) that $\text{C/O} \sim 0.9$ M dwarfs are less than 1% appears to be supported too. However, the methods of analyses are so different that the comparison of the results remains only qualitative.

5. Conclusion

Recently carbon and oxygen abundances of 46 M dwarfs have been obtained respectively from CO and H₂O molecular lines (Tsuji & Nakajima 2014; Tsuji et al. 2015; Tsuji & Nakajima 2016). This is not a differential abundance analysis with respect to the Sun. We present C/O ratios and kinematics of these M dwarfs. The distribution of C/O ratios in M dwarfs is compared with those in solar type stars obtained by Nissen et al. (2014), Delgado Mena et al. (2010), and Petigura & Marcy (2011) using the K-S test. The distribution C/O ratios in M dwarfs and that by Nissen et al. (2014) are consistent with being drawn from a same distribution, while the distributions by Delgado Mena et al. (2010) and Petigura & Marcy (2011) are not drawn from the same distribution as that in M dwarfs. High solar C/O ratios adopted by Delgado Mena et al. (2010) and Petigura & Marcy (2011) partly explain these results.

Since carbon and oxygen abundances of solar type stars have been obtained by differential analyses with respect to the Sun, pairs of C/O ratio distributions with respect to the solar ratio, are compared among those by Takeda & Honda (2005), Nissen et al. (2014), Delgado Mena et al. (2010) and Petigura & Marcy (2011). The distributions by Takeda & Honda (2005) and Nissen et al. (2014) are consistent and those by Delgado Mena et al. (2010) and Petigura & Marcy (2011) are barely consistent, while other pairs are mutually inconsistent. Larger scatters in C/O distributions by Delgado Mena et al. (2010) and Petigura & Marcy (2011) are explained by the use of [OI] 6300 forbidden line as the abundance indicator of oxygen.

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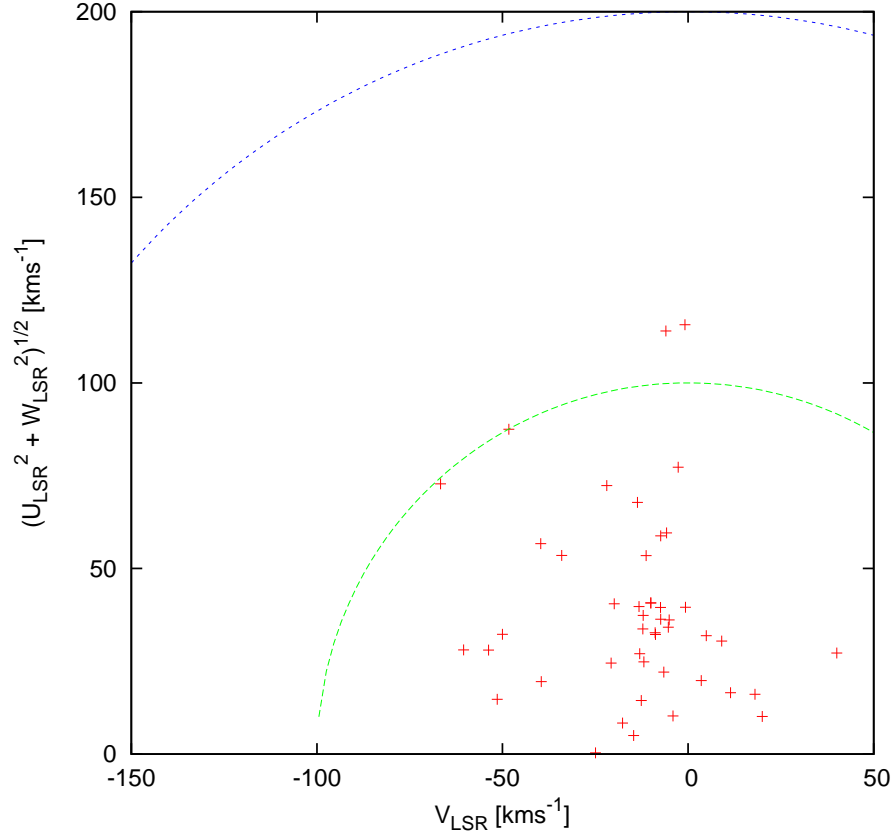


Fig. 1.— Toomre diagram for the sample M dwarfs. The green and blue lines are for $|\mathbf{V}|_{\text{LSR}} = 100$ and 200 km s^{-1} respectively. Most of the stars have thin disk kinematics, while two stars possibly have thick disk kinematics ($|\mathbf{V}|_{\text{LSR}} > 100 \text{ km s}^{-1}$). There is no star with halo kinematics.

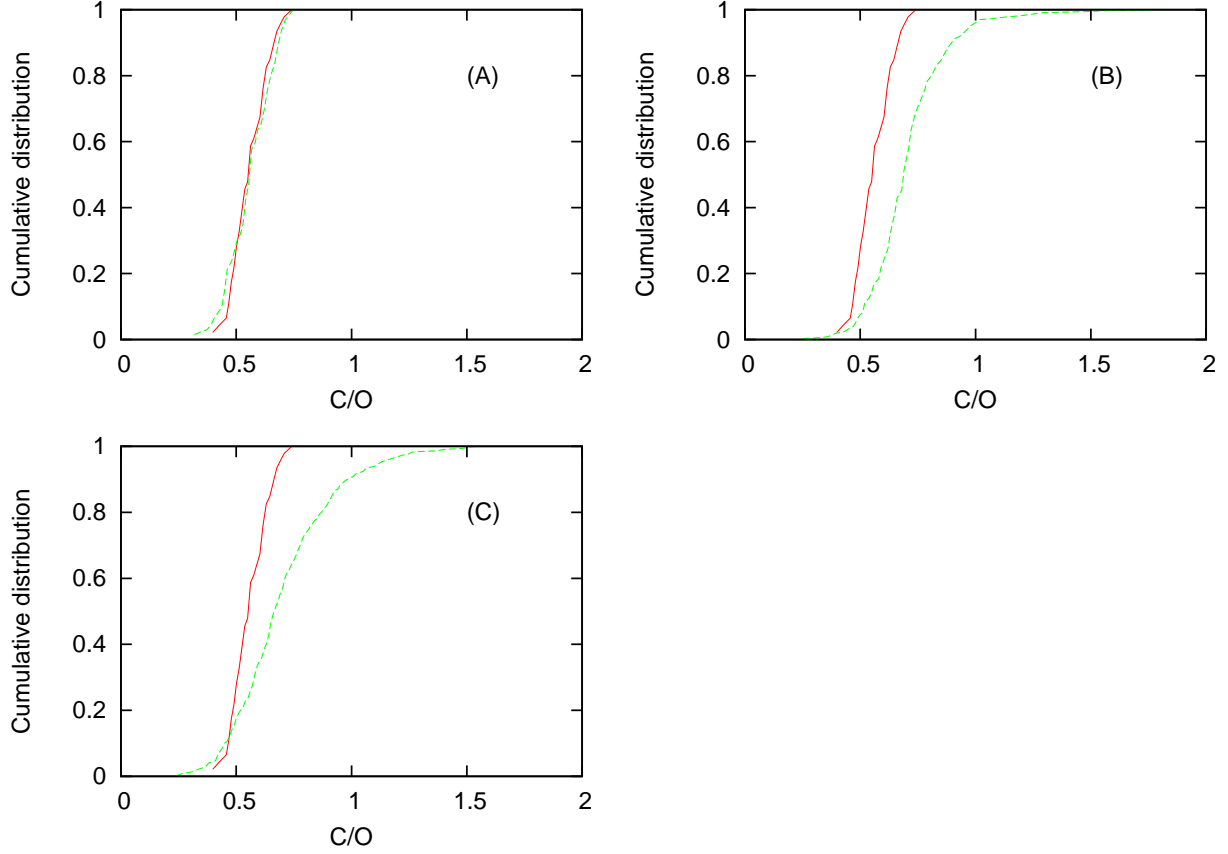


Fig. 2.— Comparison of two cumulative distributions. (A) M dwarfs (red) and Nissen et al. (2014). (B) M dwarfs (red) and Delgado Mena et al. (2010) (green). (C) M dwarfs (red) and Petigura & Marcy (2011). The probability that each pair are the same is given in Table 2.

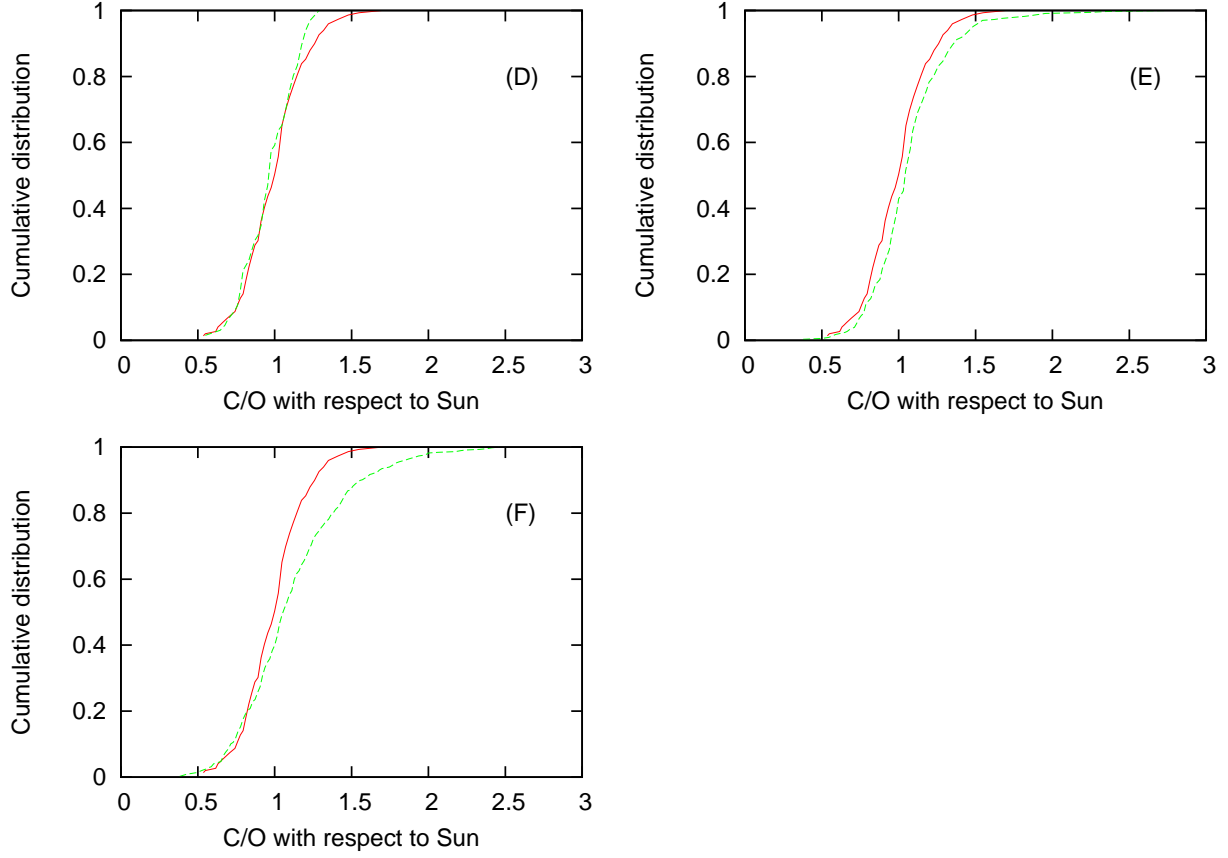


Fig. 3.— Comparison of two cumulative distributions. (D) Takeda & Honda (2005) (red) and Nissen et al. (2014) (green). (E) Takeda & Honda (2005) (red) and Delgado Mena et al. (2010) (green). (F) Takeda & Honda (2005) (red) and Petigura & Marcy (2011) (green). The probability that each pair are the same is given in Table 3.

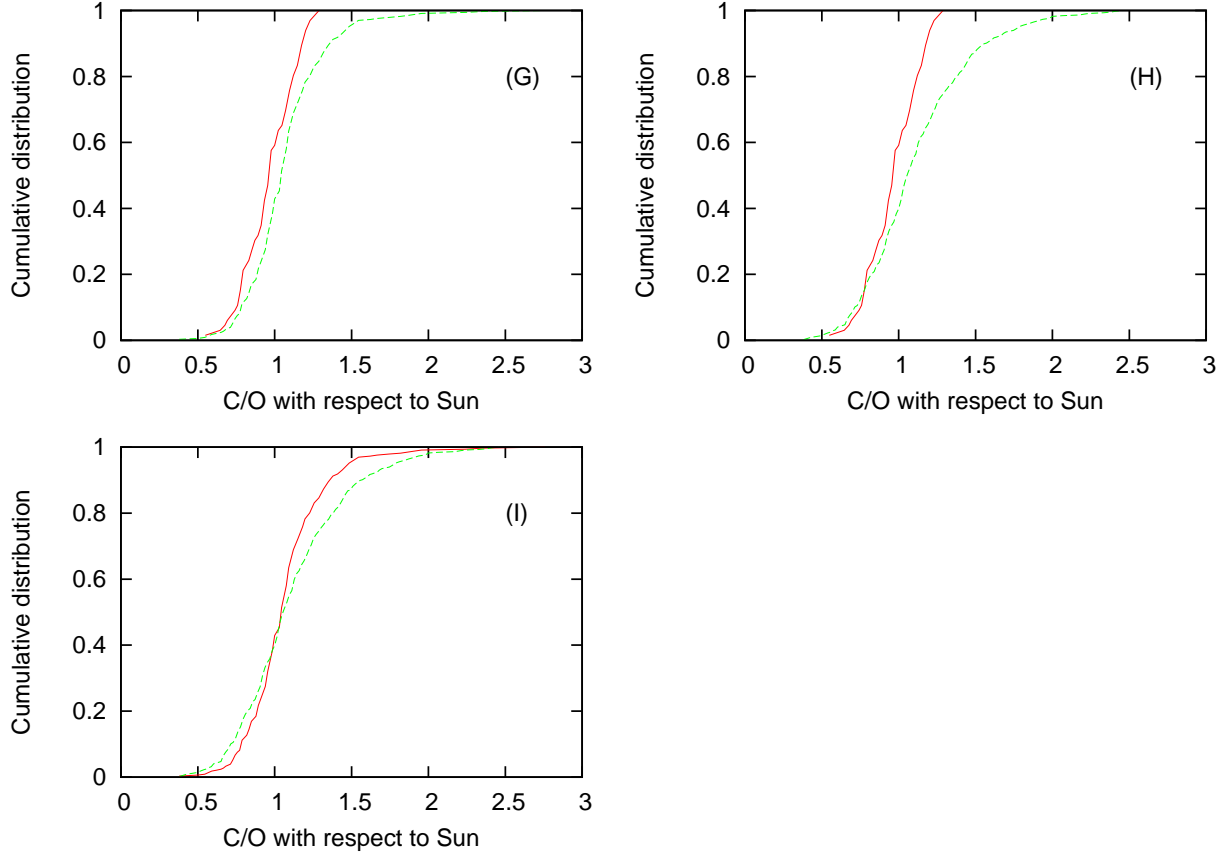


Fig. 4.— Comparison of two cumulative distributions. (G) Nissen et al. (2014) (red) and Delgado Mena et al. (2010) (green). (H) Nissen et al. (2014) (red) and Petigura & Marcy (2011) (green). (I) Delgado Mena et al. (2010) (red) and Petigura & Marcy (2011) (green). The probability that each pair are the same is given in Table 3.

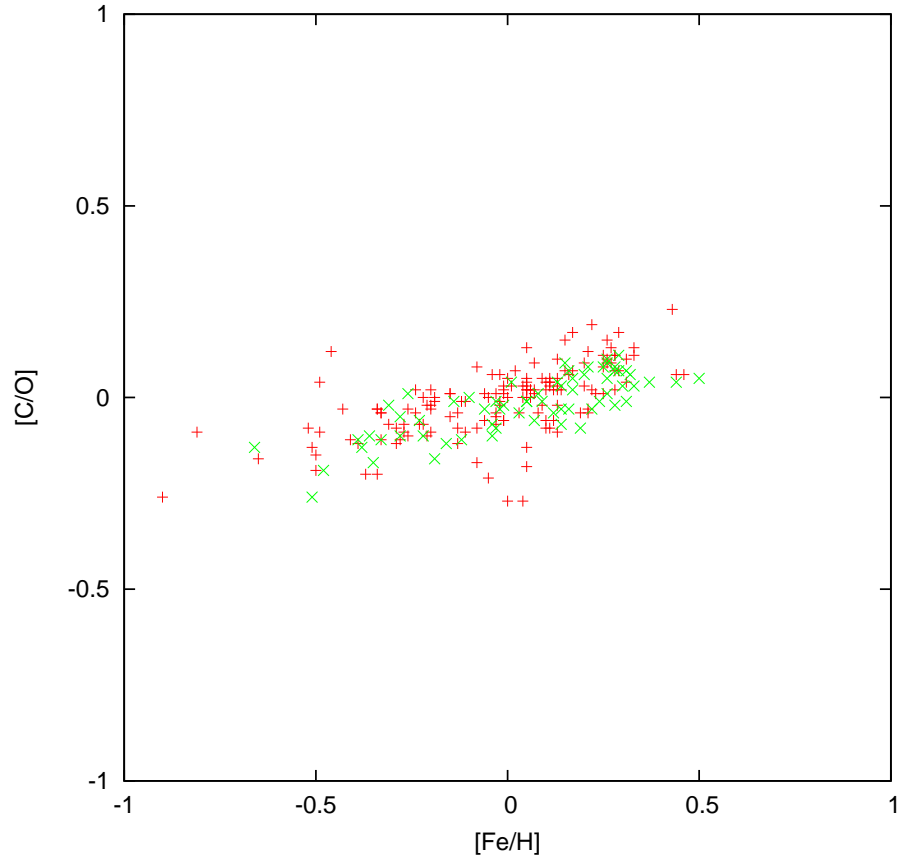


Fig. 5.— $[C/O]$ vs. $[Fe/H]$ for Takeda & Honda (2005) (red) and Nissen et al. (2014) (green).

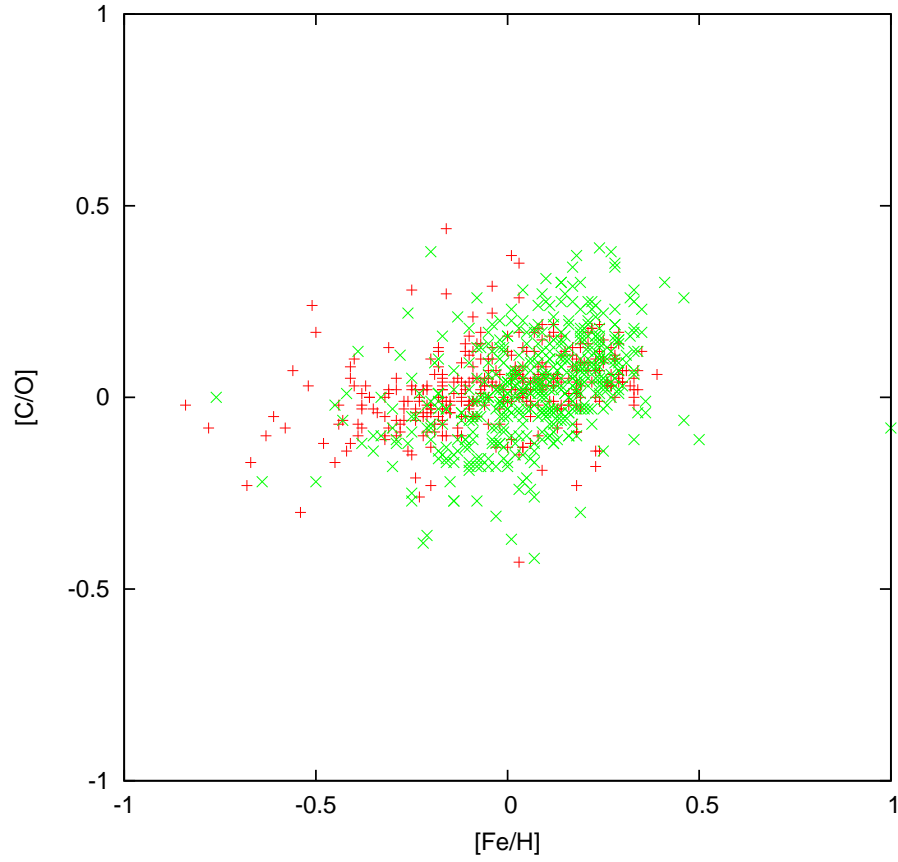


Fig. 6.— $[C/O]$ vs. $[Fe/H]$ for Delgado Mena et al. (2010) (red) and Petigura & Marcy (2011) (green) . For Petigura & Marcy (2011), $[M/H]$ is used as the substitute for $[Fe/H]$.

Table 1. Carbon and oxygen abundances and kinematics

| Object | $\log A_C$ | $\log A_O$ | C/O | U_{LSR} kms $^{-1}$ | V_{LSR} kms $^{-1}$ | W_{LSR} kms $^{-1}$ | $ \mathbf{V}_{LSR} $ kms $^{-1}$ |
|-----------|------------------|------------------|------|--------------------------|--------------------------|--------------------------|-------------------------------------|
| GJ15A | -3.60 \pm 0.11 | -3.31 \pm 0.01 | 0.51 | -39.3 | -7.5 | 4.3 | 40.2 |
| GJ105B | -3.47 \pm 0.06 | -3.14 \pm 0.04 | 0.47 | -69.2 | -2.7 | 34.3 | 77.3 |
| GJ166C | -3.37 \pm 0.14 | -3.03 \pm 0.06 | 0.46 | 108.8 | -6.0 | -34.0 | 114.1 |
| GJ176 | -3.35 \pm 0.07 | -3.15 \pm 0.02 | 0.63 | -12.8 | -51.4 | -7.3 | 53.5 |
| GJ179 | -3.43 \pm 0.11 | -3.18 \pm 0.04 | 0.56 | 23.5 | -11.9 | 8.0 | 27.5 |
| GJ205 | -3.12 \pm 0.08 | -2.97 \pm 0.05 | 0.71 | 32.1 | -50.0 | -3.2 | 59.5 |
| GJ212 | -3.30 \pm 0.11 | -3.10 \pm 0.03 | 0.63 | -4.6 | -17.6 | -7.0 | 19.5 |
| GJ229 | -3.27 \pm 0.07 | -3.10 \pm 0.02 | 0.68 | 21.6 | -6.6 | -4.8 | 23.1 |
| GJ231.1B | -3.57 \pm 0.05 | -3.24 \pm 0.05 | 0.47 | -10.0 | 20.0 | -1.6 | 22.4 |
| GJ250B | -3.41 \pm 0.10 | -3.19 \pm 0.03 | 0.60 | 9.5 | 18.0 | -13.0 | 24.1 |
| GJ273 | -3.40 \pm 0.11 | -3.13 \pm 0.04 | 0.54 | 26.2 | -60.5 | -9.9 | 66.7 |
| GJ324B | -3.36 \pm 0.13 | -3.17 \pm 0.04 | 0.65 | -27.0 | -13.1 | 0.1 | 30.0 |
| GJ338A | -3.59 \pm 0.04 | -3.32 \pm 0.03 | 0.54 | -29.4 | -8.8 | -13.2 | 33.4 |
| GJ338B | -3.58 \pm 0.04 | -3.31 \pm 0.06 | 0.54 | -34.1 | -12.1 | -15.2 | 39.3 |
| GJ406 | -3.61 \pm 0.10 | -3.40 \pm 0.03 | 0.62 | -16.1 | -39.6 | -11.0 | 44.1 |
| GJ411 | -3.67 \pm 0.06 | -3.37 \pm 0.03 | 0.50 | 55.7 | -48.3 | -67.5 | 100.0 |
| GJ412A | -3.85 \pm 0.04 | -3.53 \pm 0.03 | 0.48 | -113.0 | -0.9 | 24.8 | 115.7 |
| GJ436 | -3.63 \pm 0.06 | -3.42 \pm 0.02 | 0.62 | 62.5 | -13.7 | 26.3 | 69.2 |
| GJ526 | -3.55 \pm 0.04 | -3.28 \pm 0.03 | 0.54 | 59.1 | -5.8 | 7.1 | 59.8 |
| GJ581 | -3.56 \pm 0.05 | -3.26 \pm 0.03 | 0.50 | -14.7 | -20.7 | 19.6 | 32.1 |
| GJ611B | -3.76 \pm 0.03 | -3.36 \pm 0.06 | 0.40 | -25.9 | -53.7 | -10.6 | 60.6 |
| GJ649 | -3.54 \pm 0.04 | -3.34 \pm 0.03 | 0.63 | 31.6 | -8.9 | 8.3 | 33.9 |
| GJ686 | -3.50 \pm 0.04 | -3.23 \pm 0.03 | 0.54 | -23.6 | 40.1 | -13.5 | 48.4 |
| GJ687 | -3.43 \pm 0.09 | -3.22 \pm 0.03 | 0.62 | 40.5 | -19.9 | 0.2 | 45.1 |
| GJ725A | -3.58 \pm 0.09 | -3.27 \pm 0.05 | 0.49 | -14.7 | -7.4 | 33.2 | 37.1 |
| GJ725B | -3.61 \pm 0.08 | -3.29 \pm 0.06 | 0.48 | -13.8 | -5.1 | 33.4 | 36.5 |
| GJ768.1C | -3.50 \pm 0.08 | -3.20 \pm 0.04 | 0.50 | 8.2 | 3.6 | -18.0 | 20.1 |
| GJ777B | -3.24 \pm 0.16 | -3.02 \pm 0.05 | 0.60 | -2.5 | -39.7 | -56.6 | 69.2 |
| GJ783.2B | -3.41 \pm 0.10 | -3.14 \pm 0.05 | 0.54 | -20.6 | -21.9 | 69.3 | 75.6 |
| GJ797B-NE | -3.54 \pm 0.09 | -3.28 \pm 0.03 | 0.55 | -32.8 | -10.1 | 24.1 | 42.0 |
| GJ797B-SW | -3.51 \pm 0.09 | -3.26 \pm 0.03 | 0.56 | -32.8 | -10.1 | 24.1 | 42.0 |
| GJ809 | -3.55 \pm 0.04 | -3.37 \pm 0.03 | 0.66 | 31.9 | -5.3 | -12.2 | 34.6 |
| GJ849 | -3.27 \pm 0.09 | -3.09 \pm 0.02 | 0.66 | -32.6 | -12.2 | -8.4 | 35.9 |
| GJ876 | -3.36 \pm 0.13 | -3.14 \pm 0.04 | 0.60 | -2.4 | -14.7 | -4.4 | 15.5 |
| GJ880 | -3.35 \pm 0.07 | -3.18 \pm 0.03 | 0.68 | 42.7 | -11.3 | 32.1 | 54.6 |
| GJ3348B | -3.40 \pm 0.11 | -3.08 \pm 0.05 | 0.48 | 0.3 | -25.0 | 0.1 | 25.0 |
| HIP57050 | -3.26 \pm 0.12 | -3.05 \pm 0.04 | 0.62 | -12.0 | -12.6 | -8.0 | 19.2 |
| HIP79431 | -3.24 \pm 0.12 | -3.11 \pm 0.01 | 0.74 | 9.1 | -4.1 | -4.7 | 11.0 |
| GJ54.1 | -3.38 \pm 0.09 | -3.13 \pm 0.06 | 0.56 | -8.3 | -0.7 | 38.7 | 39.6 |
| GJ752B | -3.55 \pm 0.07 | -3.31 \pm 0.04 | 0.58 | 58.8 | -7.4 | 1.7 | 59.2 |
| GJ873 | -3.44 \pm 0.09 | -3.13 \pm 0.06 | 0.49 | 30.0 | 9.1 | 5.2 | 31.8 |
| GJ1002 | -3.42 \pm 0.09 | -3.17 \pm 0.05 | 0.56 | 46.5 | -34.0 | 26.5 | 63.4 |
| GJ1245B | -3.44 \pm 0.10 | -3.15 \pm 0.07 | 0.51 | 15.9 | 11.4 | -4.5 | 20.1 |
| GAT1370 | -3.78 \pm 0.06 | -3.41 \pm 0.06 | 0.43 | -55.4 | -66.7 | -47.2 | 98.7 |
| LP412-31 | -3.36 \pm 0.07 | -3.20 \pm 0.03 | 0.69 | -36.9 | -13.2 | -14.8 | 41.9 |

Table 1—Continued

| Object | $\log A_C$ | $\log A_O$ | C/O | U_{LSR} kms ⁻¹ | V_{LSR} kms ⁻¹ | W_{LSR} kms ⁻¹ | $ \mathbf{V}_{LSR} $ kms ⁻¹ |
|-----------|------------|------------|------|--------------------------------|--------------------------------|--------------------------------|---|
| 2M1835+32 | -3.57±0.20 | -3.32±0.03 | 0.56 | 31.7 | 4.9 | 3.3 | 32.3 |

Table 2: The Kolmogorov-Smirnov test between M dwarfs and others

| Distribution 1 | Distribution 2 | D | Probability ^a | Panel ^b |
|----------------|---------------------|-------|--------------------------|--------------------|
| M dwarfs | Nissen et al. | 0.177 | 3.30×10^{-1} | A |
| M dwarfs | Delgado Mena et al. | 0.528 | 1.29×10^{-10} | B |
| M dwarfs | Petigura & Marcy | 0.427 | 2.60×10^{-7} | C |

^aProbability that the two distributions are the same. If this value is less than 0.01, the two distribution are regarded as different.

^bPanel in Figure 2 In each panel, distribution 1 is in red and distribution 2 is in green.

Table 3: The Kolmogorov-Smirnov test among differential analyses

| Distribution 1 | Distribution 2 | D | Probability ^a | Panel ^b |
|---------------------|---------------------|-------|--------------------------|--------------------|
| Takeda & Honda | Nissen et al. | 0.121 | 4.87×10^{-1} | D |
| Takeda & Honda | Delgado Mena et al. | 0.163 | 7.26×10^{-3} | E |
| Takeda & Honda | Petigura & Marcy | 0.204 | 1.40×10^{-4} | F |
| Nissen et al. | Delgado Mena et al. | 0.234 | 3.80×10^{-3} | G |
| Nissen et al. | Petigura & Marcy | 0.288 | 1.02×10^{-4} | H |
| Delgado Mena et al. | Petigura & Marcy | 0.114 | 1.27×10^{-2} | I |

^aProbability that the two distributions are the same. If this value is less than 0.01, the two distribution are regarded as different.

^bPanel in Figures 3 and 4. In each panel, distribution 1 is in red and distribution 2 is in green.